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Reduction of Pollutant Emissions for Industrial Boilers by Combustion Modification

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16. ABSTRACT The paper describes results of a field test program to investigate the usefulness of combustion modification in reducing NOx emissions from industrial boilers (ranging in size from 11 to 528 GJ/hr). The gaseous and particulate emissions from coal, oil, and natural-gas fuels were measured both before and after the combustion modification. Data were taken on particulate size as well as concentration. The principal combustion modification methods investigated included reduced excess combustion air, staged combustion air, recirculated flue gas, tuned burners, and reset burner registers. Staging was implemented by using overfire air ports or by turning off the fuel to some burners and increasing the fuel to others, thus creating zones of fuel-rich combustion. All of the combustion modification methods were effective to varying degrees in reducing the NOx emissions, and reductions of as much as 50% were obtained with several of the modifications. In most instances boiler efficiency was not degraded, although the particulate emissions increased by up to 50% in some cases. There was no substantive effect on the other pollutant emissions that were measured.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution Dust	Pollution Control	13B 11G
Fossil Fuels	Stationary Sources	21D
Combustion Control	Combustion Modification	21B
Boilers	Industrial Boilers	13A
Nitrogen Oxides	Particulate	07B
Flue Gases		21B

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Reduction of Pollutant Emissions From Industrial Boilers by Combustion Modification

The use of combustion modification has enabled many utility boilers to meet the emission standards for NO_x. Its usefulness in reducing NO_x emissions from industrial boilers (ranging from 11 GJ/hr to 528 GJ/hr) has been investigated during a recently completed field test program. The gaseous and particulate emissions from coal, oil, and natural-gas fuels were measured both before and after the combustion modification. Data were taken on particulate size as well as concentration. The principal combustion modification methods that were investigated included reduced excess combustion air, staged combustion air, recirculated flue gas, tuned burners, and reset burner registers. Staging was implemented by the use of overfire air ports or by turning off the fuel to some burners and increasing the fuel to others, thus creating zones of fuel-rich combustion. All of the combustion modification methods were effective to varying degrees in reducing the nitrogen oxides emissions, and reductions of as much as 50 percent were obtained with several of the modifications. In most instances the boiler efficiency was not degraded, although the particulate emissions increased by up to 50 percent in some cases. There was no substantive effect on the other pollutant emissions that were measured.

The objective of this 2-year program of field testing sponsored by the U. S. Environmental Protection Agency[1] was to determine the gaseous and particulate emission levels and the efficiency of industrial boilers ranging in capacity from 11 to 527 GJ/hr (10,000 to 500,000 lb of steam per hour) [1].[2] An additional objective was to determine if the NO_x emissions could be reduced significantly by modifying the combustion process in the proper manner while still maintaining (or improving) boiler efficiency [2].

The results of the field testing of 19 combinations of boilers and fuels were used to establish design and/or operational changes that boiler manufacturers and operators could make to reduce emissions and to determine where future combustion research activities should be concentrated.

The following emissions were measured:

Emission	Technique
Total nitrogen oxides, NO_x	Chemiluminescence
Hydrocarbons, HC	Flame ionization
Carbon monoxide, CO	Nondispersive infrared
Carbon dioxide, CO_2	Nondispersive infrared
Sulfur dioxide, SO_2	Shell-Emeryville (wet)
Sulfur trioxide, SO_3	Shell-Emeryville (wet)
Particulate concentration	EPA Standard Method 5
Particulate size	Cascade impactor
Plume opacity	EPA Standard Method 9
Smoke	Bacharach smoke spot
Boiler efficiency	ASME heat loss

Baseline Test Results

The baseline emissions were measured first to establish the general level of emissions from industrial boilers as a class and then to provide a base level from which to determine the effect on emissions of subsequent combustion modifications.

NO_x Emissions. The primary categorization of boilers was by steam output or size, and one objective was to determine whether the larger boilers had the greater emissions. The NO_x emissions were found to be slightly dependent on boiler size, as indicated in Fig. 1; however,

[1] This report has been reviewed by the U.S. Environmental Protection Agency and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

[2] Numbers in brackets designate References at end of paper.

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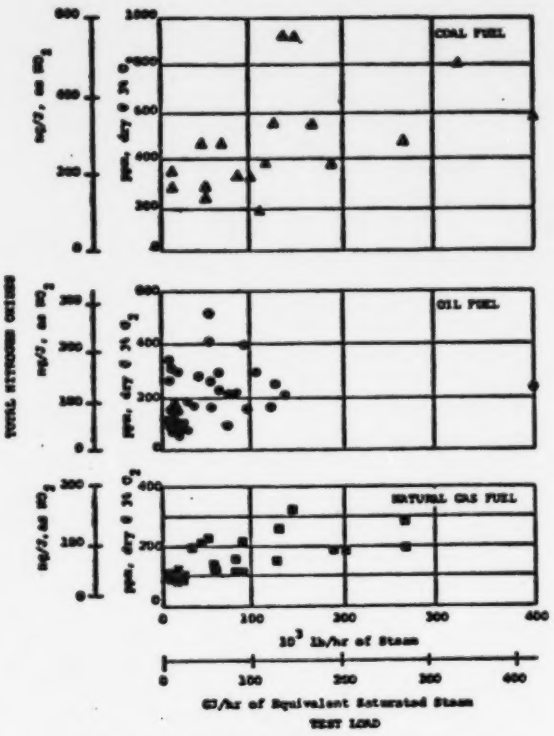

Fig. 1 Total oxides of nitrogen emissions at baseload

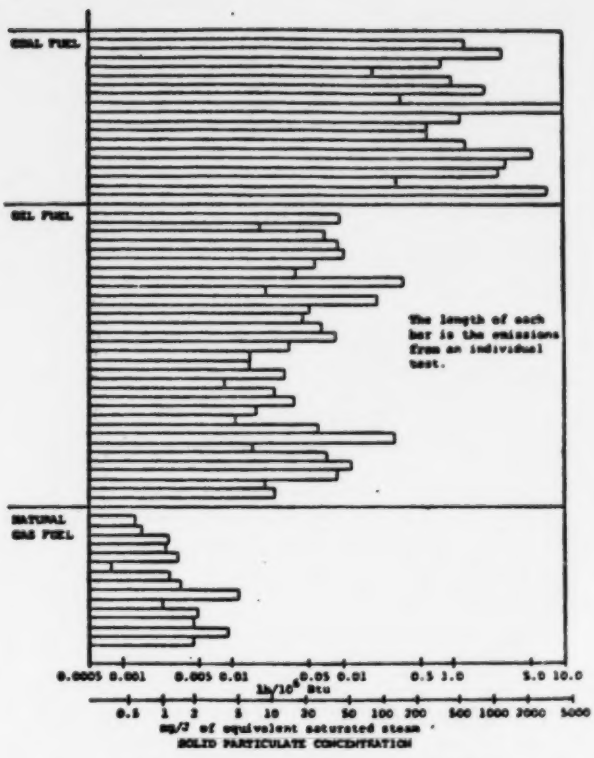
COAL FUEL
OIL FUEL
NATURAL GAS FUEL
The length of each bar is the emissions from an individual test.
lb/10^6 Btu
ng/J of equivalent saturated steam
SOLID PARTICULATE CONCENTRATION

Fig. 2 Solid particulate emissions at baseload

they were strongly dependent on type and nitrogen content of the fuel being fired. This strong dependence is illustrated in Table 1, which shows the range and average concentration of nitrogen oxides emissions. Coal fuel was the chief emitter of NO_x.

Solid Particulate Emissions. The solid particulate emissions were not at all dependent on the boiler size, but they were strongly dependent on the fuel type, as Fig. 2 shows. The emissions from coal were about 10 times greater than those from oil and about 100 times greater than those from natural gas.

Particulate Size. The size distribution of the particulates was measured to determine the effect on size of fuel type, burner type, and combustion modification. Eleven representative measurements are listed in Table 2 that were made with oil fuel and 13 with coal fuel using the Brink model B low-speed-flow-type cascade impactors. Usually the soot that accumulated during a size test was sampled by blowing soot just before the start and finish of a test (however, it was not blown during the particulate emission measurements).

Table 1 Range and average emissions of total nitrogen oxides at baseline and at low-NO_x operation

	Range	Average Emissions			
	Baseline	Baseline Operation		Low NOx Operation	
Fuel Type	NOx ng/J (ppm @ 3% O_2)	NOx ng/J (ppm @ 3% O_2)	O_2 %	NOx ng/J (ppm @ 3% O_2)	O_2 %
Coal	180-542 (164-922)	390 (475)	8.7	225 (369)	6.7
No. 2 Oil	36-101 (65-180)	67 (130)	5.5	59 (105)	4.0
No. 5 Oil (Pre 300)	112-347 (200-619)	164 (293)	5.8	142 (254)	4.9
No. 6 Oil	107-196 (190-350)	151 (269)	5.3	121 (216)	4.9
Natural Gas	36-191 (50-375)	71 (139)	4.8	57 (111)	5.0

Table 2 Distribution of particulate size

OIL FUEL

Test		Proportion of Total Weight of Catch				
Load GJ/hr (10^3 lb/hr)	Burner or Oil Type	Particles Inhaled Thru Inhaled <0.5 μm %	Particles In The "Fine" Particulate Size Range <3 μm %	Particles Reducing Visibility by Mie Scattering 0.4-0.7 μm %	Soot Included	Test Conditions
90 (85)	PS300	60	81	30	No	Baseline
76 (72)	No. 6	20	60	8	Yes	Baseline with light soot
76 (72)	No. 6	25	70	20	Yes	Baseline with light soot
76 (72)	No. 6	3	20	3	Yes	Baseline with heavy soot
37 (35)	No. 6	7	40	6	No	Baseline
68 (64)	No. 2	1	26	1	No	Baseline
53 (50)	No. 6	40	73	3	Yes	Baseline
53 (50)	No. 6	27	67	3	Yes	Baseline
54 (51)	No. 6	25	65	3	Yes	Baseline
69 (65)	No. 6	32	62	3	No	Higher load
34 (32)	No. 6	20	50	1	No	Baseline

COAL FUEL

97 (92)	Spbit	6.7	8	<1	No	Baseline, Upstream of Cyclone
432 (408)	Pulv.	2	20	3	No	Baseline, Downstream of Cyclone
136 (128)	Short	12	34	6	No	Baseline, Downstream of Dust Collector
111 (105)		48	68	13	Yes	
111 (105)		25	33	3	Yes	
130 (124)		6	20	2	Yes	
106 (100)		5	22	2	Yes	
126 (120)		8	25	4	Yes	
140 (132)	Pulv.	3	20	1	Yes	Baseline, Upstream of Dust Collector
140 (132)		1	20	<1	Yes	Baseline, Downstream of Dust Collector
140 (132)		1	11	3	Yes	Baseline, Upstream of Dust Collector
140 (132)		1	16	2	Yes	Baseline, Downstream of Dust Collector
140 (132)		<1	17	<1	Yes	Baseline, Downstream of Dust Collector

Table 3 Combustion modification methods and effects

CATEGORY AND METHOD	EFFECT
1. Fuel-Air Ratio Variation	
• Excess air level	• Varies the overall fuel to air ratio
• Air staging	• Creates local fuel to air ratio stratification by bypassing air and delaying complete combustion
• Burners-out-of-service	• Creates local fuel to air ratio stratification by bypassing air and delaying complete combustion
• Burner register adjustment	• Controls swirl and the local rate of fuel and air mixing
2. Enthalpy Variation	
• Combustion air temperature	• Influences peak gas temperature level and duration
• Flue gas recirculation	• Reduces peak gas temperature level and duration
• Firing rate	• Affects fuel heat release rate per unit volume, and gas heat loss rate
3. Input Variation	
• Fuel oil temperature and viscosity	• Controls atomization characteristics, e.g., drop size and vaporization rate
• Fuel type switching	• Reduces sulfur and/or nitrogen oxides emissions from the fuel
• Burner tune-up	• Assures performance according to design specifications
• Fuel oil atomization method and pressure	• Controls local fuel and air mixing rates by varying drop size distribution and overall fuel spray shape

Particulates having diameters of 3 μm or less that are listed in the fourth column are important because these "fine" particulates are inhaled readily and tend to deposit in the body's air passages [3]. The catch in the fine particulate range ran from about 30 to 80 percent by weight for oil fuel. For coal fuel the proportion was less, about 20 to 33 percent, with one instance of 65 percent.

Oil fuel also produced more particulates in the size range of 0.4 to 0.7 μm than did coal; these sizes of particulates cause reduced visibility and an atmospheric haze. As expected, the particulates from coal had larger aerodynamic diameters than did the particulates from oil.

Hydrocarbon Emissions. Hydrocarbon emissions from both natural gas and oil fuels generally were low and in the range of 0 to 14 ng/J (zero to 75 ppm).

Carbon Monoxide Emissions. The baseline carbon monoxide emissions for industrial boilers were normally near zero, although in a few test cases the boilers were being operated with over 70 ng/J (200 ppm) of carbon monoxide emissions.

Sulfur Oxides Emissions. Almost all of the sulfur present in the fuel appeared in the stack gases, and the level of sulfur oxides emissions was directly proportional to the sulfur content of the fuel. There appeared to be an exception with some high-sulfur coals. In these cases the sulfur oxide content of the stack gas was below 100 percent conversion, indicating that a portion of the sulfur may have been emitted in another form. For instance, it may have been retained in the flyash or emitted as a sulfate in the flue gas.

Boiler Efficiency. Baseline ASME heat-loss efficiencies for coal-fired boilers ranged from 72 to 88 percent and averaged 81 percent. The oil-fired boilers exhibited efficiencies between 72 and 88 percent and averaged 83 percent. Gas-fueled boilers had efficiencies from 70 to 85 percent, with an average of 81 percent.

The larger-capacity boilers were more efficient than smaller units, probably because of more efficient design. The type of burner had an influence on efficiency in the case of coal-fired units. Cyclone and pulverizer units had much higher efficiency levels than did the chain-grate and underfed stokers.

Combustion Modification Test Results

The three major categories of combustion modification and the 11 modification methods that were investigated are listed in Table 3. While the principal objective of combustion modification was to reduce the emissions of NO_x, the effects of the modifications on the other emissions (such as hydrocarbons and particulates) and on boiler efficiency were considered too. It was found that combustion modification did not increase the other gaseous emissions to any extent, but it did have a significant effect on the particulate emissions and on the boiler heat-loss efficiency. The limit of the extent to which any combustion modification method could be applied was that the carbon monoxide emissions could not exceed about 34 ng/J (100 ppm). The criterion of 100 ppm of carbon monoxide was used because in most instances carbon monoxide levels increase rapidly beyond this point.

The effects on NO_x, boiler heat-loss efficiency, and particulate concentration are summarized for all of the combustion modification methods in Figs. 3 and 4. Each chart is divided into quadrants, two of which are labeled Best Quadrant and Worst Quadrant. With respect to NO_x and boiler efficiency, the criterion for the best quadrant is that the NO_x emissions decrease but the efficiency increases. In the worst quadrant the opposite occurs. With solid particulates, both the NO_x and particulate emissions decrease in the best quadrants.

Nitrogen Oxides and Particulate Emissions. *Excess Combustion Air.* The best combustion modification method on the basis of ease of implementation, emission reduction, and efficiency was to reduce the amount of excess air being fired. In about 72 percent of the instances where the excess air was reduced the nitrogen oxides emissions decreased and the boiler efficiency increased. The NO_x decreased by up to 38 percent of the baseline level, and the efficiency increased by up to 3 percentage points.

The test results of changing the level of excess oxygen on the total

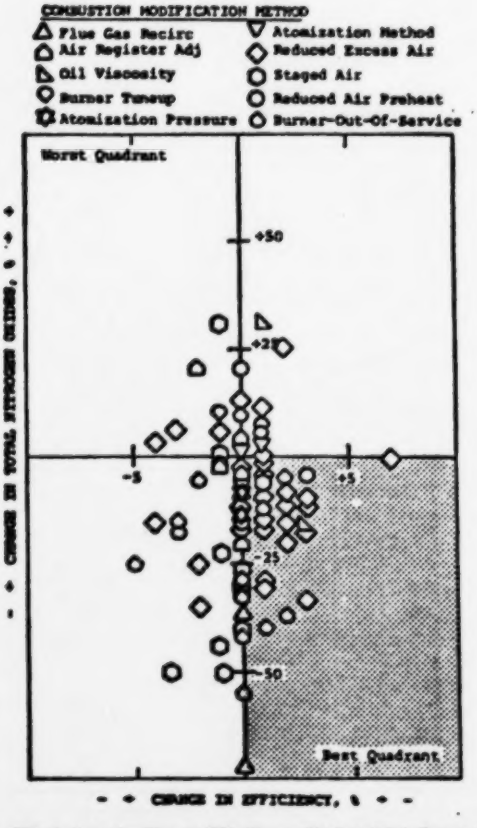

Fig. 3 Effect of combustion modification method on total nitrogen oxides emissions and boiler efficiency.

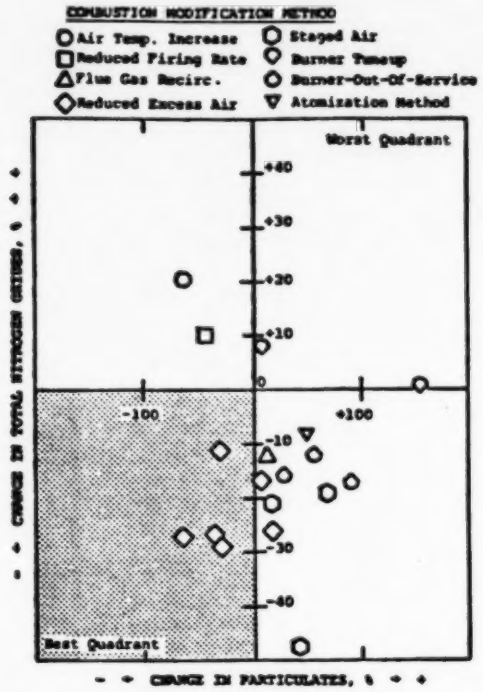

Fig. 4 Effect of combustion modification method on total nitrogen oxides and solid particulate emissions

nitrogen oxides emissions are depicted in Fig. 5. The effect of reducing the excess oxygen was greatest for coal fuel, causing a reduction in NO_x level of about 12 percent for each percentage point reduction in excess oxygen.

The effect on the solid particulate emissions was to reduce them by up to 15 percent with coal fuel and up to 30 percent with No. 6 oil fuel. The criterion for minimum excess air was when the carbon monoxide emissions exceeded 100 ppm, and with this criterion in no case did the particulate increase.

Staged Combustion Air. Nine tests were run where the combustion air was added in stages: three each on coal, oil, and gas fuels. In all but two cases, staging the air reduced the nitrogen oxides emissions by up to 47 percent. One exception was with natural gas fuel, where the change was zero, and the other was a spreader stoker, where the nitrogen oxides emissions increased by 10 percent. In four cases the boiler efficiency decreased up to 3 percentage points, and in the other five cases it was unchanged.

Diverting some of the combustion air from the initial combustion zone at the burner and injecting it farther downstream from the burner had two principal effects on the formation of nitrogen oxides. First, the combustion process was slowed down and the consequent delayed release of the heat of combustion resulted in a lower temperature for the products of combustion; thus formation of the thermal nitrogen oxides was suppressed. Second, less oxygen was available in the initial flame zone, and this suppressed the formation of nitrogen oxides from the fuel nitrogen.

On three of the staged air tests with No. 6 oil, the particulate concentration was measured with and without staged air, and in all cases the particulate emissions increased by 12 to 75 percent. Apparently, delaying complete combustion increased the amount of unburned carbon in the flue gas.

Two boilers were modified to allow adding part of the air downstream of the burner, and five boilers were tested that had been manufactured with staged air capability.

One of the staged air modifications installed in a 47-GJ/hr (45,000-lb/hr steam flow) vertical-type watertube boiler is diagrammed in Fig. 6. A 36-cm-dia manifold pipe was run along each side of the boiler and was connected to a fan mounted on the floor. Four flexible-fabric pipes were connected to the manifold, and these could be connected to the five staged air ports that had been cut into the furnace side walls on each side. The results of the tests on this boiler with natural gas fuel are presented in Fig. 7. The results indicate the following for gas fuel: (1) For the ports located along the burner axis (ports 6–13) the nitrogen oxides emissions exhibited little sensitivity to the location of staged air addition. (2) The staged air ports located 1 m above the burner axis and at the rear of the furnace (ports 14 and 15) were the most effective in reducing nitrogen oxides, (3) The nitrogen oxides reduction with staged air addition was a strong function of the ratio of the actual amount of air at the burner to stoichiometric or theoretical air.

The nitrogen oxides emissions from gas fuel were reduced from the baseline level of 112 ng/J (220 ppm)[3] to 91 ng/J (175 ppm) simply by decreasing the excess air. They were reduced further to about 80 ng/J

[3] All NO_x data reported in parts per million (ppm) have been corrected to 3 percent excess O_2.

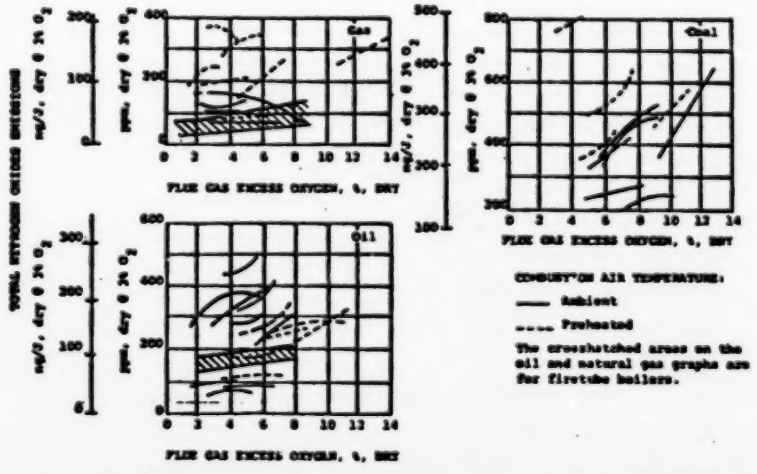

Fig. 5 Reduction in total nitrogen oxides emissions due to a decrease in excess oxygen

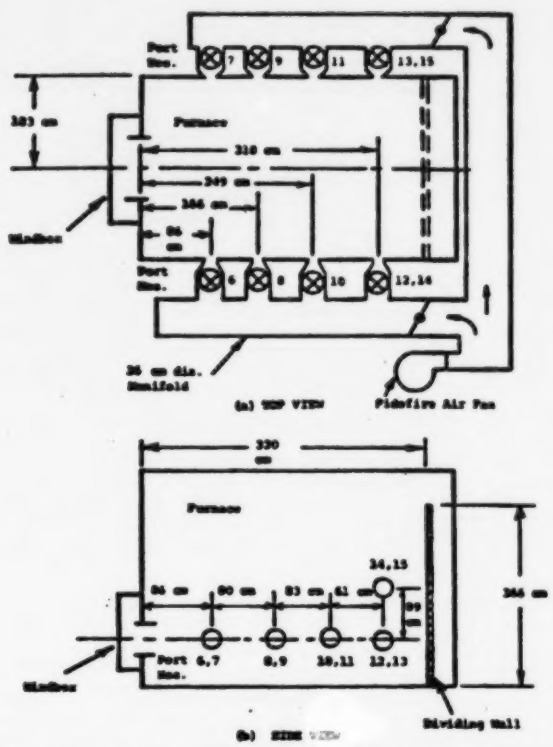

Fig. 6 Schematic diagram of staged combustion air system installed on a 47-GJ/hr (45,000-lb/hr steam flow) vertical-type watertube boiler

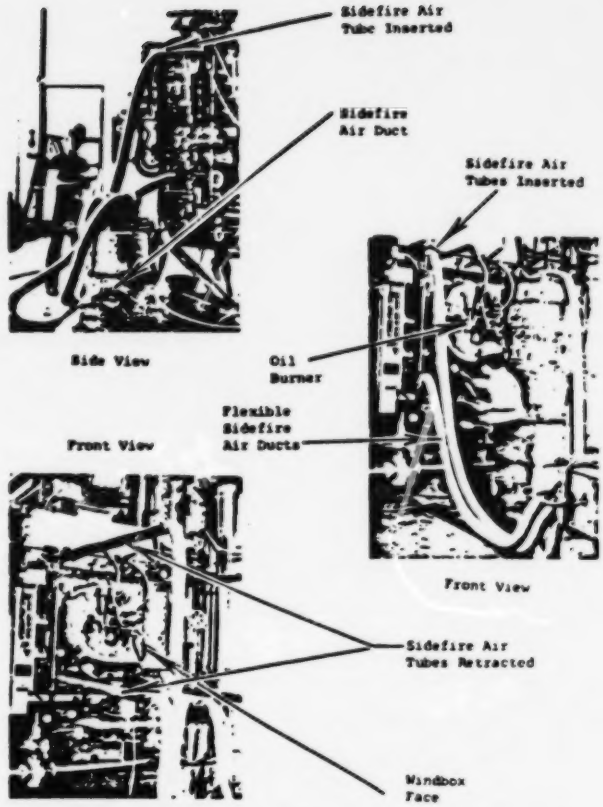

Fig. 8 Staged combustion air installation on a 18.5-GJ/hr (17,500-lb/hr steam flow) watertube boiler

(157 ppm) by staging the air through the middle ports. When the air was staged through the upper rear ports (Nos. 14 and 15) the NO_x emissions were reduced still further to 52 ng/J (102 ppm), for a total reduction of 54 percent. By trimming the combustion air it was possible to achieve this 54 percent reduction and limit the carbon monoxide emissions to less than 34 ng/J (100 ppm).

There was a stronger effect of the location at which the staged air was added on the NO_x emissions from oil than from gas. The ports farther back caused a relatively greater reduction in NO_x than did the forward ports. Apparently, moving the injection location away from the oil burner provided a lower heat release rate and a longer residence time of the combustion products in the cooler fuel-rich region than it did with gas fuel. In addition, the longer residence time under fuel-rich conditions allowed a greater fraction of the nitrogen compounds in the oil fuel to be reduced to molecular nitrogen rather than be oxidized to nitric oxide, thus also decreasing the fuel NO_x.

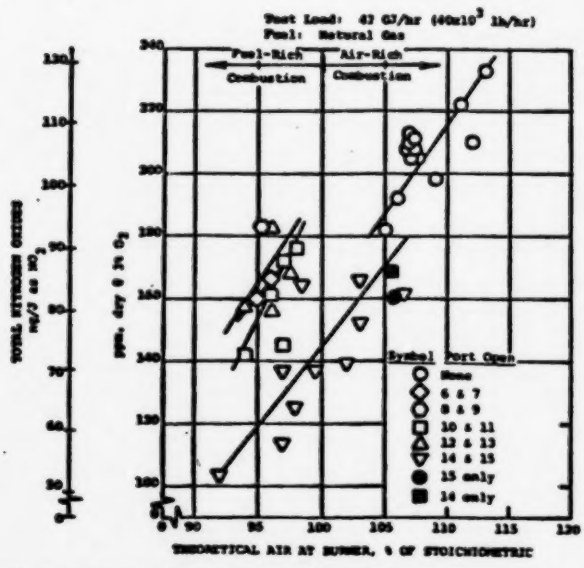

Fig. 7 Reduction of NO_x due to staged combustion air, natural gas fuel, 47-GJ/hr (45,000-lb/hr steam flow) vertical-type watertube boiler

The second boiler, a D-type water tube unit rated at 18.5 GJ/hr (17,500 lb/hr steam flow), was modified such that the staged air was introduced into the furnace by four steel tubes that were inserted through holes cut into each of the four corners of the windbox. Flexible ducts were attached to the end of each overfire air tube to supply air from the staged air duct to each tube, as shown in Fig. 8. A representative effect of staged air on nitrogen oxides emissions for steam-atomized No. 6 fuel oil firing is shown in Fig. 9. The data grouping at the upper right is from baseline and excess air reduction tests. The lowest nitrogen oxides emission level that could be obtained merely by reducing the excess air was 90 ng/J (160 ppm) with 108 percent theoretical air.

When part of the air was introduced into the combustion zone only 30 cm downflame of the burner, there was no reduction in nitrogen oxides emissions relative to the baseline. When the injection point was moved 121 cm into the furnace and the theoretical air at the burner was reduced to 80 percent, the emissions dropped to 61 ng/J (108 ppm). This was a 36 percent drop from the baseline emissions and a 13 percent drop from the lowest emissions obtainable by reducing the excess air.

The nitrogen oxides reductions with the oil- and the gas-fueled burners where the staged air ports were built into the furnace side wall

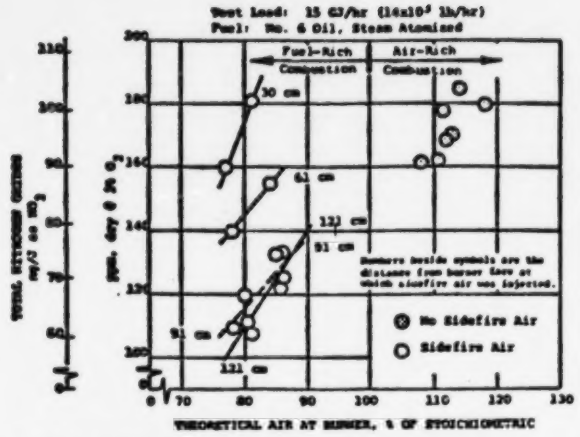

Fig. 9 Reduction in NO_x due to staged combustion air, No. 6 oil fuel, 18.5-GH/hr (17,500-lb/hr steam flow) watertube boiler

and were not adjustable were 10 and 40 percent, respectively.

Burner Out of Service. The form of staged combustion that produced the greatest NO_x emission reduction was operation with one of the burners out of service. In this mode the fuel, but not the air, was turned off on one of the burners. The total amount of fuel being burned was held constant by redistributing the fuel to the other burners. The result was that the other burners were operating fuel-rich, and complete combustion was delayed by the surplus of fuel and the scarcity of air.

With a burner out of service the NO_x emissions decreased by 9 to 54 percent (see Fig. 3). The wide range of reduction was due to variations in the amount of staging from boiler to boiler. An advantage of this combustion modification was that the boiler efficiency was relatively unaffected and varied by only ±0.5 percentage points over nine runs. A disadvantage was that the combustion process was distributed such that the particulate emissions always increased. In one case the increase was about 54 percent, and in a second case the increase was about 95 percent for a comparable reduction in NO_x emissions. In addition, modifications to the fuel delivery system may be necessary in order to achieve full load while operating with a burner out of service.

The data shown in Fig. 10 are typical of the results obtained when burners were taken out of service. For example, on a 74-GJ/hr (70,000-lb/hr) natural-gas-fired boiler that had three burners in a horizontal row, it was possible to lower the nitrogen oxides emissions from the baseline level of 108 ng/J (211 ppm) to 85 ng/J (166 ppm) by simply reducing the amount of excess air with no burners out of service. Then the center burner was taken out of service, and it was possible to enter the fuel-rich burning region and reduce the nitrogen oxides emissions to 49 ng/J (96 ppm). This was a 55 percent reduction in nitrogen oxides emissions. The boiler efficiency was unaffected.

Similar results were obtained with oil and coal fuels, the reduction in nitrogen oxides ranging from 20 to 40 percent.

Burner Register Adjustment. Adjustment of the burner air registers reduced the NO_x by 6 to 22 percent. The efficiency change ranged from unchanged to as much as 1 percentage point lower, and the particulate emissions were unchanged. These results were from a series of tests where the local air/fuel mixture ratio was controlled by changing the burner air register setting and thus the amount and the swirl of the air that entered the burner.

In general, the tests involving burner air register adjustments indicated the following:

1 The major effect of register adjustments on multiple-burner units is an alteration of the air distribution between the individual burners, and not a change in swirl in the burner adjusted.

2 On single-register burners, increasing the swirl (closing registers) tends to decrease the nitrogen oxides emissions. The mixing of the cooler external circulation gases with the hot combustion-zone gases suppresses the formation of the thermal nitrogen oxides.

3 On dual-register burners the major effect of register adjustment on nitrogen oxides emissions appears to be redistribution of air between the secondary and tertiary air passages, with swirl playing a minor role.

Combustion Air Temperature Reduction. Reducing the preheating of the combustion air reduced the total nitrogen oxides by up to 32 percent, but boiler efficiency was decreased by as much as 3 percent. The combustion air temperature was systematically varied on three separate units by about 83K (150°F), and the results are depicted in Fig. 11. The solid symbols represent the normal air tem-

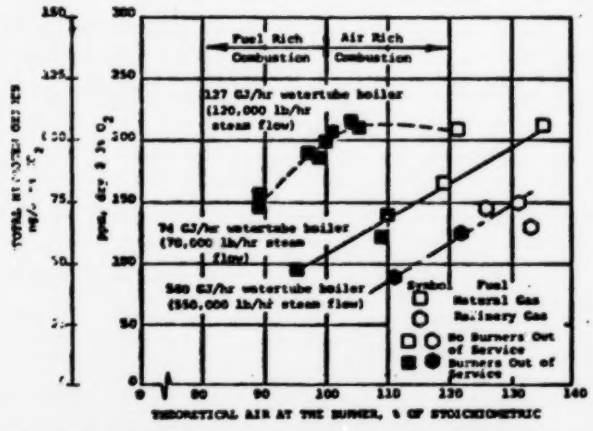
Fuel Rich Combustion
Air Rich Combustion
127 GJ/hr watertube boiler (120,000 lb/hr steam flow)
74 GJ/hr watertube boiler (70,000 lb/hr steam flow)
580 GJ/hr watertube boiler (550,000 lb/hr steam flow)
Symbol Fuel
Natural Gas
Refinery Gas
No Burners Out of Service
Burners Out of Service
THEORETICAL AIR AT THE BURNER, % OF STOICHIOMETRIC

Fig. 10 Effect of burners out of service on total nitrogen oxides emissions, natural gas and refinery gas fuel

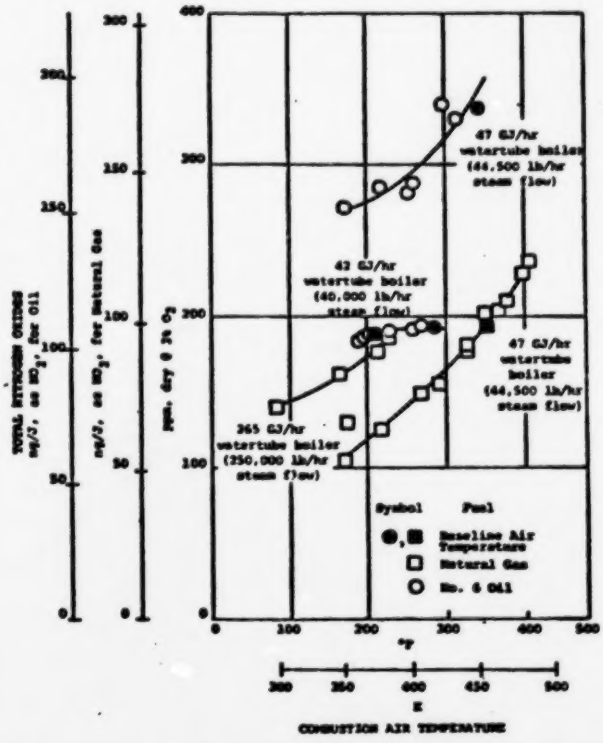
47 GJ/hr watertube boiler (44,500 lb/hr steam flow)
42 GJ/hr watertube boiler (40,000 lb/hr steam flow)
265 GJ/hr watertube boiler (250,000 lb/hr steam flow)
47 GJ/hr watertube boiler (44,500 lb/hr steam flow)
Symbol Fuel
Baseline Air Temperature
Natural Gas
No. 6 Oil
°F
K
COMBUSTION AIR TEMPERATURE

Fig. 11 Effect of combustion air temperature on total nitrogen oxides emissions, gas and oil fuels

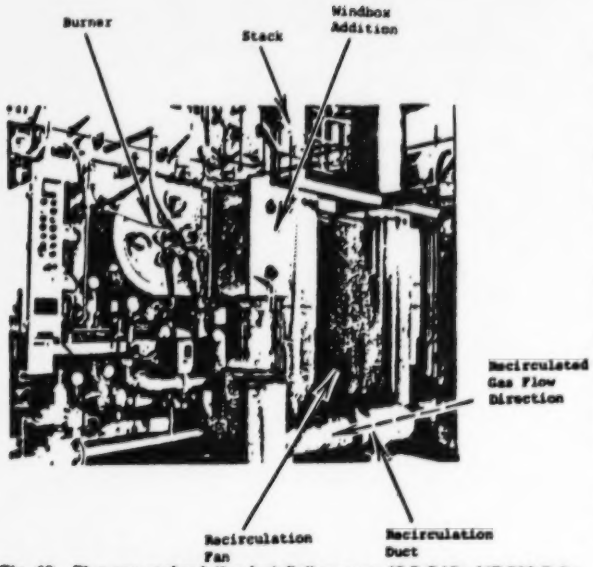

Fig. 12 Flue gas recirculation installation on an 18.5-GJ/hr (17,500-lb/hr steam flow) watertube boiler

perature. For example, during the test series with No. 6 oil firing on a watertube boiler rated at 47 GJ/hr (45,000 lb/hr steam flow), the NO_x emissions decreased by 20 percent as the combustion air temperature was reduced from about 450K to 350K (350°F to 170°F). This corresponded to a change of 23 ng/J (41 ppm) in nitrogen oxides per 50K (90°F) change in air preheat temperature.

The results were similar for both gas and oil fuels as long as the combustion was in the thermal NO_x region. When the thermal NO_x had been largely suppressed, the NO_x from oil fuel no longer decreased. This effect is seen below 400K during the test in the 47-GJ/hr (45,000-lb/hr steam flow) watertube boiler and during the entire test series in the 42-GJ/hr (40,000-lb/hr steam flow) watertube boiler.

Flue Gas Recirculation. Testing of utility-size boilers has established that the recirculation of flue gas into the combustion air reduces flame temperatures in the furnace and limits the formation of thermal nitrogen oxides. Since it also reduces the oxygen concentration in the primary combustion zone, there also may be a reduction in the conversion of fuel-bound nitrogen to NO_x.

The watertube boiler rated at 18.5 GJ/hr (17,500 lb/hr steam flow), which was modified for staged combustion, was also modified by adding flue gas recirculation capability, and the installation is pictured in Fig. 12. The flue gas was drawn from the bottom of the smoke stack by a flue gas recirculation fan and was pumped through the recirculation duct and up into the right side of the windbox through a windbox-and-burner addition that had been fabricated.

Fig. 13 shows that flue gas recirculation was successful in reducing the NO_x emissions by 10 percent with No. 6 oil. With natural gas alone, a 70 percent reduction from the baseline level was achieved. The boiler heat-loss efficiency was unaffected. There was an increase in the solid particulate concentration of about 10 percent, probably due to a slight increase in the unburned carbon in the less stable oil flame that resulted when flue gas was recirculated.

Flue gas recirculation is most effective in reducing the formation of thermal NO_x that is due to the thermal fixation of atmospheric nitrogen at elevated temperatures. Since the NO_x emission from natural gas combustion is entirely thermal NO_x, the flame temperature reduction potential of the recirculated combustion products is fully realized. However, the NO_x emission from oil combustion is due partly to the oxidation of nitrogen contained in the oil, and this oxidation is not highly dependent on the temperature of the combustion. Therefore recirculation is less effective with oil fuel.

In addition, oil fuel combustion is slower in relation to the intense burning of natural gas from a highly mixed ring-type burner. In the course of combustion a significant amount of natural recirculation of combustion products within the flame zone occurs, and the flame is self-cooled.

Testing was done to evaluate the effect of flue gas recirculation on particulate emissions from steam-atomized oils. Baseline solid particulates for steam-atomized No. 6 fuel oil were 8.6 ng/J (0.020 lb/MBtu). Operating with 16.5 percent flue gas recirculation on steam-atomized No. 6 oil resulted in a particulate increase of 10 percent to 9.5 ng/J (0.022 lb/MBtu).

Firing Rate Reduction. When the combustion was modified by lowering the firing rate (steam output) of a boiler, the total nitrogen oxides emissions increased in 16 instances and decreased in 19 instances by ± 12 to 25 percent. The increases and decreases of efficiency also were evenly divided, i.e., ± 3 percentage points. The reason for the increased nitrogen oxides emissions was that the amount of excess air being fired usually was raised at the lower firing rates. This rise in air prevailed over the NO_x reduction of the less-intense flame and caused a net increase in the NO_x emissions.

Gas-fired boilers were relatively insensitive to load changes unless they had air preheaters. Then, reductions in total nitrogen oxides of about 20 percent were realized as the firing rate was dropped from 100 percent of nameplate capacity to 50 percent of capacity. Oil-fired boilers showed little or no relationship between nitrogen oxides emissions and firing rate. Generally, coal-fired boilers showed an increase in nitrogen oxides emissions when operating below 60 percent capacity that was caused by the necessary increase in the excess air level.

Fuel Oil Temperature. Tests were conducted with No. 6 oil over an oil temperature range of 340K to 395K (155°F to 250°F). No consistent relationship was observed, although in all cases the changes in the total nitrogen oxides emissions were less than 10 percent above or below the baseline level. The boiler efficiency was increased from 1 to 3 percentage points.

Another field test crew from KVB tested a twin boiler at the same location for the effect of fuel oil temperature on particulate emissions. They found that the particulate emissions as indicated by the mass monitor showed a 57 percent decrease with increasing oil temperature and a further decrease with increased oil atomization pressure [4].

Burner Tuneup. At two test sites the field maintenance technician of the burner manufacturer tuned the burner after the baseline emissions measurements had been made. Tuneup consisted of adjusting the excess air to the proper level for each load, adjusting the

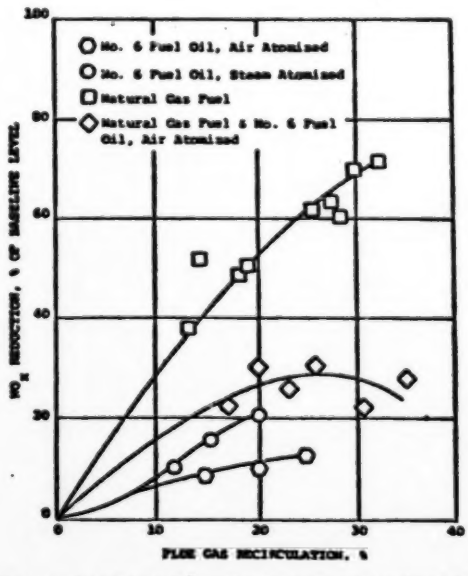

Fig. 13 Reduction in NO_x emissions by flue gas recirculation

burner registers to give a hard, bright flame, and replacing worn parts in the oil gun tips.

For both oil and gas fuels, if the burner was tuned to reduce the carbon monoxide to near zero and/or to improve the flame texture and color, the nitrogen oxides emissions either were unchanged or increased. Tuneup was universally successful in reducing carbon monoxide, however. Reducing carbon monoxide to near zero generally increased the heat input efficiency (e.g., 0.6 to 1.0 percent) because the decrease in the combustible carbon monoxide in the stack gases was slightly greater than the corresponding increase in heated air exhausted up the stack. No consistent trend in the particulate emissions was observed.

Fuel Atomization Pressure. When the fuel oil atomization pressure was increased and the boiler was at 80 percent capacity, the nitrogen oxides emissions decreased. When the same type of test was done on another boiler at a firing rate of only 25 percent of capacity, the nitrogen oxides emissions increased by 6 percent. Concurrently, the Bacharach smoke number decreased by two numbers.

In the first test the increased pressure caused a smaller apex angle of the fuel droplet cone to form. It is postulated that it took longer for the combustion air to penetrate this tighter cone and the combustion was consequently delayed. The production of nitrogen oxides was reduced. In the low-firing-rate test the tightening of the fuel droplet cone actually enhanced the burning rate of the milder flame, and the total nitrogen oxides production was increased. The ASME heat-loss efficiency was not affected significantly by variations in the atomization pressure.

The series of tests done by another KVB field test crew on a twin boiler at 80 percent capacity in the same boiler house achieved a reduction of about 50 percent in solid particulates by increasing the oil pressure from 580 to 722 kPa (70 to 90 psig). The decrease was deemed to be due to the smaller oil droplets that were formed when the atomization pressure was increased. The NO_x emissions increased by about 16 percent of this unit [4].

Fuel Atomization Method. The total nitrogen oxides emissions were found to be relatively independent of the fuel oil atomization method (i.e., steam, air, pressure, or rotary cup) and dependent on the characteristics of the individual burner. For a given oil burner the oil atomization method that produced the lowest nitrogen oxides emissions also usually produced the highest particulate emissions of the test series. The boiler efficiency was unaffected to any significant degree by the type of atomization employed. In general, the test results indicated that a well-maintained oil burner operating near its design point will produce about the same level of nitrogen oxides and particulate emissions regardless of the atomization method used.

Burner Type. It was found that the nitrogen oxides emissions were lower from certain burners; however, it was difficult to ascertain whether the differences were due primarily to the burner or to interrelated burner–boiler characteristics and fuel properties. Pulverized coal burners generally produced slightly more particulate than did stoker-equipped boilers.

Particulate Size. It was found that some types of combustion modifications affected the sizes of the particulates that were emitted. The distributions shown in Fig. 14 are representative of the effects that were observed.

The upper two curves of Fig. 14 show the effect on the particulate size distribution of modifying the combustion of oil fuel by reducing the amount of excess air/oxygen. Reducing the excess oxygen from 4.3 to 4.0 percent reduced the proportion of fine particulates from about 58 to 50 percent. The total nitrogen oxides concentration dropped from 109 to 98 ng/J (195 to 174 ppm). Apparently the modified combustion resulted in a decrease in the proportion of smaller particulates and an increase in the proportion of larger particulates.

When coal was burned on a chain grate, the effect of reducing the excess air was different. Reducing the excess air increased the proportion of fine particulates in the catch, rather than reducing them as is the case with oil fuel.

Also shown in Fig. 14 is the effect on the particulate size distribution of modifying the fuel and air mixing by resetting the burner registers.

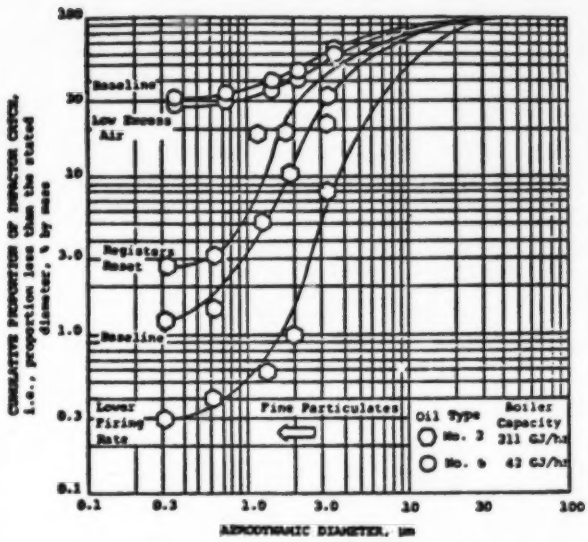

Fig. 14 Effect of combustion modification on particulate size, oil fuel

The most striking effect was that the proportion of fine particulates rose from a baseline value of about 26 percent to about 40 percent.

When the firing rate of a boiler was raised from 33 percent of capacity to 47 percent of capacity and the registers were reset for the lowest nitrogen oxides emissions, the proportion of fine particulates decreased from about 26 percent to about 5 percent. The effect of modifying combustion by tuning the burner resulted in a larger proportion of fine particulate after tuning.

Conclusions

The emissions of industrial boiler as a class are not significantly dependent on size, but they are very dependent on the fuel burned. The effect of the type of burner employed is subordinate to the effects of fuel and to the characteristics of the particular burner and boiler combination.

The nitrogen oxides emissions of the boilers tested were at or above the Stationary Source Standard [which actually applied only to new boilers larger than 63 GJ/hr (250,000 lb/hr)] in 30 to 40 percent of cases. The particulate emissions standard of 0.1 lb/MBtu was exceeded in 16 percent of the tests of oil fuel and in 100 percent of the tests of coal fuel.

The combustion modification methods that have been successful in reducing the nitrogen oxides emissions of utility boilers are also effective in reducing the emissions of industrial boilers.

On the basis of the results of the field measurements, it appears to be possible and practical to reduce the total nitrogen oxides emissions by up to 47 percent by 6 of the 11 combustion modification methods that were investigated.

However, with only three of the methods is the boiler efficiency unimpaired: excess air reduction, staged combustion with a burner out of service, and flue gas recirculation. Of these three, excess air reduction is the most attractive method because, while the nitrogen oxides reduction is only about 35 percent, the particulate emissions do not increase as they do with most of the other NO_x reduction methods, and the boiler efficiency is maintained or improved. Flue gas recirculation is promising, since the increase in particulate was only 5 percent. Staged air addition, as with burners out of service, is also somewhat promising, but considerable work will be required in distributing the air so that the particulates do not increase.

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4 Laurendeau, R., et al., "The Reduction of Particulate Emission From Industrial Boilers by Combustion Optimization," ASME Paper No. 75-WA/APC-3.